nal distribution of temperature (occasional summer condition) or to the importation of large masses of cold or warm air in rapidly moving HIGHS or LOWS or to the fact that in some instances the wind direction does not represent the original source of the air, the latter having followed a curved path round a nearly stationary HIGH or LOW.

6. Changes from north to south component winds are in nearly all cases accompanied by rising temperatures, and vice versa.

7. Owing to effects of temperature on air density, the free-air position of a LOW is usually to the northwest of its sea-level position, and that of a HIGH to the southwest. Winds therefore are southwesterly above the sea-level positions of LOWS and northwesterly above the sea-level positions of HIGHS. Under these conditions the air above LOWS is on the average warmer than that above HIGHS, the effects of importation being much greater than those of vertical movement.

8. When easterly winds prevail from the surface up to 3 or 4 kilometers, HIGHS and LOWS are either stationary or their movements are slow and erratic. Such HIGHS and LOWS are nearly circular and probably symmetrical to great heights, air circulation in them is fairly definite and steady, and the effects of vertical movement of the air are greater than those of importation, the centers of HIGHS being warmer than the centers of LOWS.

9. Since in this country symmetrical HIGHS and LOWS, referred to in (8), are less frequent than those with a westward shift of the centers, referred to in (7), it follows that the air above the sea-level positions of HIGHS is on the average colder than that above the sea-level positions of LOWS. If, however, we take the lowest and highest pressures at different heights as the basis of comparison, we find that the lowest pressures are accompanied by the lowest temperatures, the pressure itself at any level being largely a function of the mean temperature of the air column beneath.

A PRELIMINARY STUDY OF PRECIPITATION IN RELATION TO WINDS AND TEMPERATURE.

551.55 : 551.577

By V. E. JAKL, Meteorologist.

(Weather Bureau, Washington, D. C., Dec. 11, 1923.)

As a preliminary step to a more detailed study of upper-air conditions attending precipitation, a statistical study has been made of surface wind directions attending precipitation at the Drexel Aerological Station, Nebraska. The object is to reconcile the frequency, duration, and intensity of precipitation by seasons with position relative to adjoining centers of high and low pressure, or more strictly, with direction of surface isobars. Such a study should form a basis, from which, considered in connection with statistical data already compiled for the upper air, inferences may be drawn relative to the conditions of the atmosphere when precipitation is occurring.

The tabulation in Table 1, column 3, giving the frequency of precipitation in percentage for all parts of a LOW is shown in Figure 1. This figure is intended to be the simplest possible method of showing the sense of direction of the winds relative to the surface isobars; in other words, the directions in Table 1 have been oriented about the center of a composite or imaginary center of low pressure. To allow for the convergence of the arrows toward the center, the table of average deviation of free-air winds from surface winds [1] has been considered, but not strictly adhered to, an average deviation of 20° of surface winds from surface isobars being assumed for all directions and all seasons. Without going into too great detail, and giving separate recognition to the different conditions, this assumption is undoubtedly justified as a general average. Moreover, the averages for all aerological observations can not be rigidly applied to the rather special conditions prevailing during precipitation.

[1] Gregg, W. R.: An Aerological Survey of the United States. Mo. WEATHER REV. SUPPLEMENT No. 20, fig. 55, 1922.

TABLE 1.—*Frequency, amount and duration of precipitation with reference to wind direction and season.*

Direction.	Number of times precipitation occurred.	Percentage of observations for all directions.	Average amount of precipitation.	Average duration of precipitation.
SPRING.			*Inches.*	*Hours.*
N	26	11	0.29	7
NE	55	23	0.36	8
E	29	12	0.32	8
SE	46	19	0.35	6
S	22	9	0.22	4
SW	13	5	0.07	2
W	10	4	0.23	2
NW	42	17	0.25	4
SUMMER.				
N	22	7	0.19	3
NE	54	19	0.36	3
E	34	12	0.41	3
SE	57	20	0.39	4
S	26	9	0.23	3
SW	38	13	0.20	2
W	14	5	0.19	1
NW	45	15	0.22	2
AUTUMN.				
N	21	12	0.28	11
NE	44	25	0.40	9
E	15	8	0.20	6
SE	26	14	0.22	6
S	23	13	0.24	6
SW	16	9	0.22	3
W	3	2	0.05	1
NW	30	17	0.17	4
WINTER.				
N	23	20	0.11	9
NE	32	28	0.22	11
E	11	9	0.21	7
SE	17	15	0.13	9
S	9	8	0.07	6
SW	4	3	0.04	5
W	1	1	0.04	3
NW	19	16	0.15	9

The surface weather data forming the basis of this analysis cover the period of observations at Drexel from the winter of 1915–16 to the spring of 1923, inclusive. The averages for summer and autumn are therefore for a 7-year period, and those for winter and spring, for 8 years. Only measurable amounts of precipitation (0.01 inch or more) have been considered.

In the case of autumn, winter, and spring it is thought the graphs are not appreciably in error. However, for the summer season the graph should be considered as only approximate. For obvious reasons, such as thunderstorm frequency and weak pressure gradients, surface wind directions in summer are not always a reliable index to general pressure distribution. The discussion referring to the graphs will therefore be devoted mainly to the three colder seasons.

The main results of this statistical study, in so far as they relate to surface conditions, agree quite closely with those obtained by the late Dr. Anton D. Udden for Davenport, Iowa,[1] by a more laborious method. They show a maximum frequency of precipitation in the region north of the center of the LOW, although in summer this area is shifted more toward the east, if the summer graph is accepted without reservation.

There is a well-defined gap in frequency of precipitation in the southern portion of the circle, or the region of westerly to southwesterly winds, and another less pronounced gap in the northeastern portion, or region of easterly winds. The former is to be expected, both from the fact of uniform wind direction with altitude and dry sources of the wind. The gap revealed in the northeastern sector, hemmed in between two sectors of frequent precipitation, is of special interest, as the natural inference would be that the maximum frequency shown in the north should dwindle on both sides toward the south. The fact that this lull in frequency in the northeastern portion is apparent in the figures for all four seasons leads to the conviction that it is real, and not due to accident of observation or insufficient period of record. On the western side of the LOW there is considerable frequency of precipitation well down toward the south, although three of the seasonal means show a decided lessening in

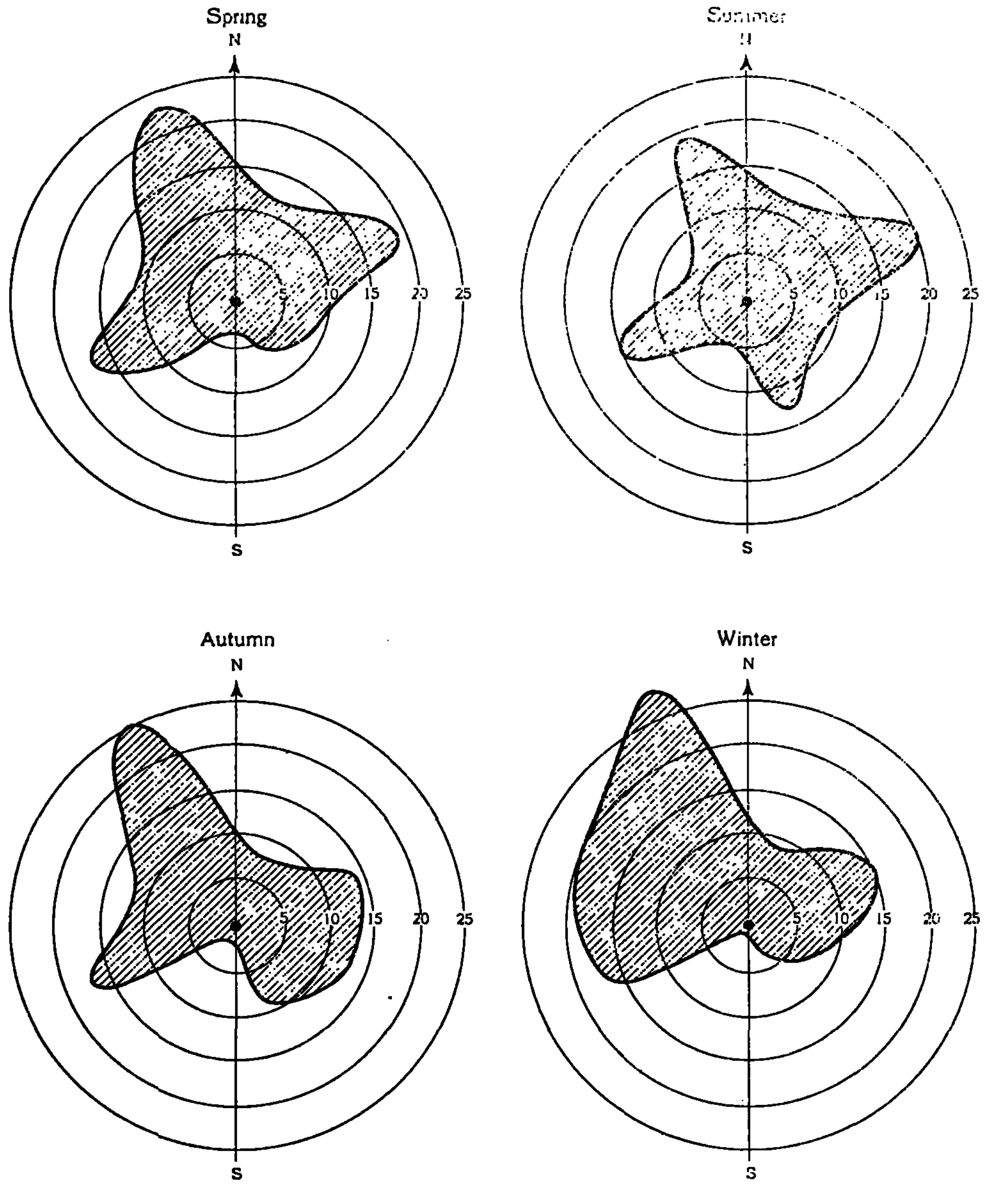

FIG. 1.—Graphical representation of third column, Table 1, showing in shaded area seasonal orientation of precipitation frequency about a center of low pressure. Figures on circles show frequency of precipitation in percentage of all observations for the season.

[1] Udden, Anton D.: A statistical study of surface and upper air conditions in cyclones and anticyclones passing over Davenport, Iowa. MO. WEATHER REV., February, 1923, 51: 55–68.

frequency in the northwestern portion, and an increase again in the southwestern portion.

A justifiable conclusion from the foregoing is that in the Missouri Valley precipitation does not occur in a haphazard way about the center of the LOW, but that there are three rather distinct circumstances of position relative to the center that favor precipitation. For convenience these may be referred to as types, viz, (a) the region of south to southeast winds in the front of the LOW; (b) the region of east to northeast winds on the northern side of the LOW; and (c) the region of north-northeast to northwest winds in the rear of the LOW, the directions all referring to surface winds. Even allowing for the nonexistence of the gap or lull in the frequency noted in the averages for spring, summer, and autumn, the inference is strong that the causes of precipitation in the rear of the LOW are different from those which account for a considerable portion occurring in the northern portion.

Referring to Figure 2, page 21, of Doctor Meisinger's work on upper air pressure reduction,[3] it will be noted that the average clockwise turning of winds with altitude is at the maximum with southeast to east surface winds, diminishing as the surface wind veers, until a counterclockwise turning occurs in the upper altitudes when the surface wind becomes northwest to northeast. Actually the greatest clockwise turning in individual cases occurs with northeast winds, the greater frequency of counterclockwise turning affecting the average. This condition of clockwise turning of winds with altitude, usually attended by stationary or falling pressure, accounts for perhaps the most of the precipitation, in amount if not in frequency, occurring with a northeast surface wind. Precipitation occurring with a northeast surface wind that backs with altitude is usually accompanied by rising pressure, and undoubtedly belongs to the general type characteristic of the rear of the LOW.

Precipitation occurring with east to northeast surface winds where the wind turns clockwise with altitude may be placed in the type defined by Bjerknes "warm front" sector,[4] this reference being to that part of Bjerknes's theory which postulates a rise of moisture-laden southerly winds up a slope of discontinuity in temperature and wind direction. A casual consideration of wind direction at the surface and aloft when this condition obtains leads to an apparently easy justification of this theory. There is, however, some evidence that precipitation does not occur precisely by the simple process pictured in this "warm front" diagram. When kite flights are made during or very close to the occurrence of precipitation in this condition, no sharp discontinuity in velocity or direction is shown by the observation; rather, it seems that precipitation begins after whatever pronounced discontinuity in wind already existing has been obliterated.

Moreover, the discontinuity in temperature called for by the Bjerknes's theory, while almost invariably observed in the lower levels in the cold season, may be only incidental to the contrasts in temperature in the lower atmosphere, characteristic of continental winters. Certainly, latitudinal temperature differences must be the prime cause of this vertical arrangement of divergent winds and attendant precipitation, yet it seems doubtful that a sharply defined stratification in either temperature or winds is a necessary condition. The aerological observations made at Drexel on June 1, 1917, July 28, 1918, and August 26, 1922, are cited as a few specimens of records in support of this assertion. These observations represent quite well the vertical distribution of temperature in this type of precipitation in the warmer season, viz, an unbroken lapse rate (except near the ground) throughout the vertical column of air embraced by the observation. Reference may also be made to some upper air investigations on this subject carried out in England [5] from which the inference may be drawn that the presence of temperature discontinuites on the European Continent and the absence of them in England under presumably the same conditions may again be incidental to the more continental and consequently colder type of HIGH peculiar to the continent. A more detailed study of the abundant aerological records now available will undoubtedly in the near future result in a satisfactory theory for this and other types of precipitation not yet adequately explained.

The precipitation belonging to the front of the LOW may be said to lie roughly between winds from about east to nearly southwest. As might be expected, rains in this segment occur generally with falling pressure, although there are many instances, particularly in summer, when precipitation with a southwest wind occurs with rising pressure and evidently belongs to a different type.

There are various ways in which precipitation on the front of the LOW can plausibly be accounted for. It is sometimes explained as being due to the convergence so frequently apparent in the directions of surface winds in this sector. This very likely explains many thunderstorms and tornadoes that occur in the southeast segment of the LOW, particularly when cold air in the lower levels has curved from the rear of the LOW. (See weather map of November 5, 1922, a. m., and aerological records at Drexel and Broken Arrow on this and the preceding date.)

Aerological observations and the circumstance of clockwise deviation of winds with altitude shown by the averages [3] suggest other processes, the ultimate cause of precipitation in all being the building up of an adiabatic gradient by winds of different sources. This may be brought about by the bringing in of cold air aloft from the rear of the storm, either directly or by a curved path (see weather map and aerological records at Drexel on November 8–9, 1917, and March 28, 1920); the bringing in of warm air in the lower levels;[6] or a combination of both. The possibility of an extension of the so-called "warm sector" type toward the south in certain formations of LOWS is also to be considered. The relatively great frequency of thunderstorms in the front of the LOW as shown by Dr. Udden's paper, which may be accepted as applying to the Missouri Valley as well, confirms the opinion that this is a region favorable for the formation of strong vertical lapse rates in temperature, presumably developed, in large measure at least, by the processes just mentioned.

Comparing the graphs for the different seasons, the winter graph shows the smallest ratio of precipitation frequency in the south and southeast portion, compared with the north portion; in fact the precipitation at this season appears to be confined largely to the north and west portions. The logical inference from this winter orientation of precipitation relative to the center of low pressure, considered in connection with Mr. Gregg's

[3] Meisinger, C. L.: The preparation and significance of free-air pressure maps for the central and eastern United States. MO. WEATHER REV. SUPPLEMENT No. 21, 1922.

[4] Bjerknes, V.: On the structure of moving cyclones. MO. WEATHER REV., February, 1919. 47: 95–99.

[5] W. H. and L. H. G. Dines: An examination of British upper air data in the light of the Norwegian theory of the structure of the cyclone. *Quarterly Journal of the Royal Meteorological Society.* July, 1923, pp. 167–173.

[6] Jakl, V. E.: Some observations on temperature and winds at moderate elevations above the ground. MO. WEATHER REV., June, 1919. 47: 371.

tables of average latitudinal temperature gradients in the lower levels,[7] is that the winter precipitation over central sections of the country is largely due to warm air aloft passing toward the north, possibly in inclined paths, and to air forcibly raised by underrunning cold air near the ground. From the average winter temperature gradient,[8] the building up of an adiabatic gradient necessary for precipitation undoubtedly necessitates, for middle-northern regions, the transport of air over comparatively long distances.

Precipitation in the rear of a LOW or front edge of a HIGH may be said to occur in connection with surface winds all the way from northeast through north and west to southwest. The relative frequency of precipitation in the rear of a LOW and front of a HIGH appears from Table 1 to be greater than that found for Davenport by Doctor Udden. This may be partially explained by referring to Figure 4, page 57 of Doctor Udden's paper, from which it may be inferred that the rain producing lows are in some later stage of development as they approach Davenport, and therefore produce a proportionately greater and more frequent precipitation over portions other than the rear of the LOW. Also it seems plausible that more frequent precipitation over the Missouri Valley than over sections to the east can be accounted for in connection with rising pressure, owing to the generally greater contrasts in temperature between high and low pressure areas over western sections than farther to the east. This point of relative frequency of precipitation in front and rear of a LOW in relation to geographic position has been referred to by Professor Cox in his discussion of forecasting in the Chicago district.[9]

Three different processes suggest themselves for explaining precipitation over those positions relative to pressure distribution where rising pressure is normally to be expected.

(*a*) An important cause of cloudiness and precipitation is to be found wherever over any extended area the wind changes to northerly. Northerly winds are inherently turbulent, a natural consequence of the overrunning of the warmer surface winds by the colder winds aloft, aided in the case of lower altitude winds, by the friction of the ground. The result is a tendency to equalization of vapor pressure throughout the vertical column, from which high relative humidity and condensation in the upper portion must follow. Over the Missouri Valley, owing to the comparative dryness of the cold winds aloft, this process probably does not often progress further than the stage of cloudiness, mists, and snow flurries. It seems highly probable, however, that in certain instances, due to the cumulative effect of passing over successively higher temperatures and vapor pressures, this may be an important cause of precipitation over sections farther to the southeast. The weather map of March 21, 1921, shows an apparent example of this process causing precipitation just to the southeast of Drexel in the front of a HIGH that had passed over Drexel without causing precipitation.

(*b*) The precipitation assumed to be caused by the underrunning effect of colder currents, entails a process that can not easily be visualized satisfactorily in all its aspects, yet there are many instances that seem to admit of no other explanation. The Bjerknes diagram and its "narrow stripe" rain, "or," "squall line" does not explain all the precipitation apparently due to underrunning cold air that occurs in this country, particularly in the colder seasons. A better idea of the three-dimensional structure of air under these conditions may be obtained by reference to Figure 31 and Chart XVIII of Doctor Meisinger's paper. Figure 31 shows a common structure of lows;[10] and Chart XVIII an apparent application of this structure to the formation of precipitation in the rear of a LOW on December 9, 1919.

Aerological observations made in pronounced cases of underrunning cold currents show the wedge-shaped altitude-temperature curves typical of cold waves. A specimen is shown graphically in a paper by V. E. Jakl, in the June, 1919, MONTHLY WEATHER REVIEW, on page 369.

Conditions along the so-called squall line appear to be a common source of precipitation in the warmer months, but the evidence of aerological observations indicates that in this case the rôle of underrunning winds is only an initiatory one, and that copious precipitation with thunderstorms in this circumstance often results from only moderate or brief pressure rises, since frequently the trough is so weak that the squall line is not defined on the weather map. One is led to conclude that in many cases a condition of instability is built up in a column of air that lacks only an initial impulse to develop into vigorous convection. Such a sequence of events is probably of common occurrence in the warmer season in connection with the passage of a trough of low pressure, where a condition of instability develops in the front, but lacks only the stimulus of an underrunning current of lower temperature, but not necessarily great depth, to culminate in active vertical convection. Illustrations, apparently confirming this view, are given by the weather maps and aerological records at Drexel on May 30–June 1, 1919, and July 25–27, 1921, and at Royal Center on March 30–31, 1921. The aerological and surface records on these dates show that while high humidity and a lapse rate in temperature approximately equal to the adiabatic rate for saturated air developed in the vertical column of air flowing from a southerly direction, precipitation was delayed until a "break" or shift in wind to northerly occurred.

(*c*) A third process of precipitation in regions of expected pressure rise, but which is perhaps confined strictly to the rear of well-defined LOWS, is that which can be inferred from a possible transport of air from the lower levels in the front of the LOW by a curved path to the rear. Especially in slow-moving LOWS, the inference is unavoidable that such circulation sometimes takes place, and if the method used by Shaw and Lempfert[11] for tracing surface trajectories is accepted as reliable, the assumption is well founded. Moreover, in some instances it is noted that when the cold air curves around to the front of the LOW, thereby cutting off the supply of warm southerly air, the precipitation in the rear ceases. (See maps of November 4–5, 1922.)

The passage of air into a region potentially colder than itself, especially when it presumably curves to the rear of a LOW, is more easily imagined than explained with a full cognizance of the dynamics of the problem involved. Undoubtedly considerable force, realized from the pressure gradient, is expended in accomplishing this result. The possibility of air rising as it approaches a colder region is also to be considered. Air that has escaped

[7] [8] Loc. cit., pp. 10 and 36–47, respectively.

[9] Weather forecasting in the United States, p. 299.

[10] In the opinion of the writer this displacement of the trough of low pressure with altitude is a function of the shape of the trough as well as the season of the year. *It is strongly* characteristic of elongated, crescent, or trough shaped lows, a point brought out by the writer on p. 246, MO. WEATHER REV., May, 1922, in a report on the "Meteorological Aspects of the Thirteenth National Balloon Race."

[11] Shaw and Lempfert: The life history of surface air currents. London, 1906.

ascent successively on the east and north sides of a LOW may reasonably be supposed to be constrained to rise after reaching the rear, as it must necessarily overrun the air of lower temperature fed into the LOW from the rear. For similar reasons air that has already risen on the east or north sides of a LOW may reach the rear and continue to rise. In this connection reference is made to the weather maps of October 27, 1918, and November 29, 1919, where, so far as surface maps may be taken as evidence, the circumstance of precipitation in the rear of a LOW, where the pressure was actually falling, indicates the possibility of air being forcibly drawn from the front to the rear of the LOW. On both maps it will be noted that the usual rise in temperature in the front of the LOW has extended well to the north of the LOW.

Of these two dates, aerological records are available for November 29, 1919, from Drexel and Broken Arrow, Okla., the observations at both stations having been taken near the ending of the precipitation. An approximately isothermal state to 2,400 meters, and a moderate lapse rate thereafter to 3,500 meters, is shown in the vertical column over Drexel, while over Broken Arrow a pronounced lapse rate is shown to 1,800 meters and an inversion immediately above. The temperatures were the same at 1,800 meters over Drexel and Broken Arrow. The lower limit of altitude at Drexel at which precipitation had occurred and to which surface air from around the front and north of the LOW had been transported is probably defined at about 2,400 meters. Over Broken Arrow, which was then in the southwest portion of the LOW, precipitation is explained by the adiabatic gradient extending from the ground upward. This gradient probably extended above 1,800 meters earlier in the storm, as a second observation made on the same date showed rising temperature aloft.

A significant fact in connection with the generally greater and more frequent precipitation in spring than in autumn, is the spring upper-air temperatures as shown by the averages.[8] The lag in the recovery of temperature aloft in spring is shown by the temperature records for all northern aerological stations for March and April, and a month earlier for the southern stations. It is graphically shown for Drexel in Figure 2, page 3, MONTHLY WEATHER REVIEW, January, 1920.[12] This fact was alluded to by the writer in a previous paper [13] as indicating conditions of instability in certain circumstances of spring weather. A statistical study might show a preponderance of Pacific HIGHS at this time of year, the Pacific HIGHS showing a greater average vertical lapse rate in temperature than do those of northern origin.

[12] Gregg, W. R.: Average free-air conditions as observed by means of kites at Drexel Aerological Station, Washington, Nebr., during the period November, 1915, to December, 1918, inclusive. MO. WEATHER REV., January, 1920, 48: 1-11.

[13] Jakl, V. E.: A kite flight in the center of a deep area of low pressure. MO. WEATHER REV., April, 1920, 48: 198-200.

551.508 (729.5)

PILOT-BALLOON OBSERVATIONS AT SAN JUAN, PORTO RICO.

By OLIVER L. FASSIG, Meteorologist.

[Abstract of an informal talk before the Weather Bureau staff meeting, Washington D. C., of January 9, 1924.]

Doctor Fassig, who is in charge of the Weather Bureau service in the West Indies, presented to the Weather Bureau staff on his recent visit to Washington, D. C., a summary of the results of pilot balloon observations made at San Juan, P. R., under his supervision during the four hurricane seasons of 1920, 1921, 1922, and 1923.

San Juan, as explained by Doctor Fassig, is favorably situated with respect to the conduct of pilot balloon work. The station is well within the northeast trade region of the North Atlantic and the sky conditions are such that an ascent to 4 or 5 kilometers can be made on about 90 per cent of the days. The trades carry the balloon in a westerly direction until it reaches the so-called antitrades of the levels above 5 or 6 kilometers; it is then carried back over the observing station almost directly overhead.

A diagram was presented showing the wind direction for each day from August 29 to October 2, 1923. On nearly 50 per cent of the days the balloons reached an altitude of 10 kilometers or over. The diagram is reproduced as Figure 1.

This diagram clearly shows that in the lower levels, up to at least 4 kilometers the winds were uniformly from an easterly direction. Occasionally, as on August 13–15 and again on August 29–30, reversals set in above the 3 kilometer level and continued for a day or so. Sometimes these reversals extend to the surface, but in the 1923 season there was but a single westerly wind observed at the surface, viz, that on August 29. The gradient at times of reversal must be very weak, since at levels above about 6 kilometers easterly and westerly winds occur nearly in equal proportion—see the period August 13–21. On rare occasions the west winds form a solid current up to the top of the ascent, on one occasion in the season of 1922 a solid SW. wind was observed from 3 to 13 kilometers.

The average wind velocity.—The inset on Figure 1 shows the average wind velocity for each month of the year from the surface up to the highest point reached. The averages for January to May, inclusive, and for December, are based upon a single year's observation, the remaining months are based on 4 years, except that June is for but 3 years. For so short a period the curve is a remarkably uniform one, with two pronounced maxima and two minima.

The group of wind roses in Figure 2 on the right shows the wind direction and frequency, in percentages, for the levels, surface up to 10 kilometers.

The curve in the center of the figure represents the average wind speed in m. p. s. all months and levels, surface up to 14 kilometers. Above that level the observations were not plentiful enough to yield a reliable average. The wind roses on the left show the direction and average speed of the wind in meters per minute up to 9 kilometers for a single season only. The wind roses on the right are also for a single season.

On October 2, 1923, a pilot balloon was observed continuously for 186 minutes. The trajectory of the balloon is shown in Figure 3. Assuming a rate of ascent of 180 meters per minute the elevation reached by this balloon must have been more than 33 kilometers. Since Doctor Fassig had some misgivings as to the accuracy of this result, he submitted the data of the ascent to the aerological investigations branch of the Central Office of the Weather Bureau for comment. The discussion that followed is given in full below. It is hoped to present a detailed discussion of the San Juan pilot balloon ascent in the near future.—*A. J. Henry.*